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Experimental efforts of proving the concept of increasing sensitivity of HTS detectors by pinning vortices started last year were continued. The major effort was directed to producing devices with random or periodic pinning defects in order to pin vortices and at the same time increase critical current. This work is in progress now. Unfortunately, the devices produced so far by heavy ion irradiation did not show consistent improvement in the critical currents at low magnetic fields, therefore, the photoresponse studies did not show consistent improvement in the responsivity. A variety of materials and samples were produces and tried. Thin films used in the studies include YI3CQ films grown at AT&T Bell Labs by coevaportion (BaF9, Thallium-based films grown at Sandia National Labs, and Hg-based films grown at University of Kansas (in progress). Samples were irradiated at Sandia National Labs (88 MeV Aug15), Los Alamos National Laboratory (3 MeV Au˜15), and Argonne National Laboratory (1.4 238 67+ 0eV U and 3.9GeV Au˜29).

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Development of Novel High Temperature Superconducting Detectors Based on Flux Activation and Ultrafast Dynamics

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ORIGINAL OBJECTIVES: STATEMENT OF WORK

- It is proposed to study quasiparticle (QP) relaxation dynamics and flux mechanism of HTS using pump/probe femtosecond spectroscopy and nonequilibrium photoresponse in the presence of a magnetic field (and/or bias current). By adding a magnetic field, the number of vortices in a superconductor will be significantly increased. The first investigation will be to determine how quasiparticle-vortex interaction changes the QP relaxation process. The second investigation will be to study interactions of high energy quasiparticles and phonons with vortices, to understand the energy transfer mechanism from the electrons and phonons to vortices, and to determine vortex core excitation energy levels, as well as vortex motion (dissipation) time constant. The studies of QP relaxation dynamics and flux mechanism will help to determine the intrinsic speed limit of a superconducting detector, and help the construction of a sensitive flux activation detector.

- Special focus, will be on the study of HTS with the high pinning density. It was demonstrated in principal that it is possible to significantly increase the number of pinning sites (defects) and simultaneously increase critical current density (by increasing vortex activation energy, U_0), using ion irradiation. However, this process should be improved and optimized. Novel approaches to accomplish this will be explored. Increasing pinning density in HTS will help to design flux activated detectors as well as help to solve a rather fundamental problem of increasing the critical current density of HTS.

- Based on the results of studies outlined above and intrinsic mechanism of the optical response, a high speed (on the order of a ns/ps response time) and sensitive flux activation detector covering a broad electromagnetic spectrum (e.g., from ultraviolet to infrared and beyond) will be developed. Also the detection mechanism of the

nonequilibrium response of a HTS to the absorption of the incident photon(s) by the measurement of the altered dynamic conductivity will be investigated.

STATUS OF THE EFFORT

Experimental efforts of proving the concept of increasing sensitivity of HTS detectors by pinning vortices started last year were continued. The major effort was directed to producing devices with random or periodic pinning defects in order to pin vortices and at the same time increase critical current. This work is in progress now. Unfortunately, the devices produced so far by heavy ion irradiation did not show consistent improvement in the critical currents at low magnetic fields, therefore, the photoresponse studies did not show consistent improvement in the responsivity. A variety of materials and samples were produces and tried. Thin films used in the studies include YBCO films grown at AT&T Bell Labs by coevaportion (BaF_2), Thallium-based films grown at Sandia National Labs, and Hg-based films grown at University of Kansas (in progress). Samples were irradiated at Sandia National Labs (88 MeV Au^{+15}), Los Alamos National Laboratory (3 MeV Au^{+15}), and Argonne National Laboratory (1.4 GeV$^{238}U^{67+}$ and 3.9 GeV Au^{+29}).

An example of results is demonstrated below. We compare two samples of a good quality. The 900Å thick films were grown at AT&T Bell Labs by coevaportion (BaF_2) process resulting in excellent crystallinity (evidenced by back-scattered minimum yield of 2% by ion channeling). YBCO 50×50μm^2 thick devices were patterned using a stripe geometry. The first device (sample 1) was studied as is, and the second device (sample 2) was ion irradiated using 88 MeV Au^{+15} ions with corresponding matching magnetic fields of 1 Tesla. Figure 1 shows resistance vs. temperature plot for two samples under study. It is seen that T_c is slightly reduces for the sample 2 after heavy ion irradiation. Figure 2 shows maximum photoresponse to 100 fs pulses from Ti:S laser of the same energy recorded by 50 GHz oscilloscope as a function of dc bias current, I_b, for these two samples at 85K. Photoresponse is increased by a factor of 5 for the sample 2. This increase could be attributed to better flux pinning (with subsequent flux unpinning by optical pulses; mechanism is described by Frenkel, PRB 48, 9717, 1993) in the sample 2 as well higher critical current (and therefore, operating bias current) which is illustrated in Figure 3. Figure 3 shows the dependence of the device resistance measured simultaneously with the photoresponse (Fig. 2) as a function of the bias current, I_b. The deparing critical current is higher for the sample 2 (42 mA vs. 32 mA). Since photoresponse is proportional to I_b, that leads to about 32% increase in the photoresponse. However, this is not enough to account for much more significant increase in the photoresponse of sample 2 shown in Figure 2. The other reason for the photoresponse increase could be better vortex pinning in the sample 2. This is evidenced by a smaller "leakage" resistance in sample #2 (1.1Ω vs. 2Ω at deparing critical current) in Figure 3. This "leakage" resistance is most likely caused by the flux creep and motion, therefore, vortices are pinned better in sample 2 which leads to increasing effectiveness of the unpinning process and to increasing photoresponse shown in Figure 2.

Another study was concentrated on resistive (real part of impedance) vs. inductive (imaginary part of impedance) components in the photoresponse and relaxation times associated with these components. Figure 4 illustrates a typical resistive photoresponse with the relaxation time on the order of 8 ns (sample 2 at 85K). This resistive component is reduced to a 1 ns range for thinner devices (40-50 nm in thickness) which is verified experimentally. When the bias current is reduced, the inductive component starts to dominate with much faster relaxation (50-100ps) which is illustrated in Figure 5 (sample 2 at 83K). Here the current is reduced from 60 mA (mixture of resistive and inductive components in Figure 5a) to 20 mA (domination of the inductive component in Figure 5c). Furthermore, the magnetic field dependence of the photoresponse, especially for the inductive component, was studied in detail. It turned out that this component has a faster increase (faster than expected from simple 2-fluid consideration) with the magnetic field, which is illustrated in Figure 6. The photoresponse transient signal in Fig. 6 is amplified by a 33dB low noise amplifier. Interpretation of these results is in progress, which is described in Appendix A.

FUTURE WORK

Based on these results and original objectives (statement of work) the future work will include the following directions:

- development of materials with periodic arrays of pinning sites using nanoscale lithography and improving the parameters of materials with random pinning using ion irradiation suitable for photodetector applications
- study the mechanism of enhancement of photoresponse by pinning of vortices
- vortex and quasiparticle relaxation dynamics studies by ultrafast optical techniques in magnetic fields
- optimization of device parameters for fast heat removal
- development of high pinning site density materials using periodic arrays and ion irradiation to increase sensitivity: a) optimize flux activation effects; b) maximize bias current.
- optimize heat removal by minimization of boundary resistance between the film and substrate and by device shape optimization (e.g., thickness, stripe geometry)
- studies of photon detection by sensing the change in optical conductivity

PERSONNEL

The following personnel was supported:
Anatoly Frenkel, PI
Gerald Sherman, technician
Alexei Semenov, postdoc
Chris Montoya, undergraduate student
Miguel Martinez, undergraduate student
James J. Vredenburg, undergraduate student

Daniel Esquibel, undergraduate student

The following collaborations have been developed and continued:

Quanxi Jia, Los Alamos National Laboratory, device fabrication, YBCO thin film deposition.
Eugene L. Venturini, Sandia National Laboratory, SQUID magnetometry and ion irradiation
Wai-Kwong Kwok, Argonne National Laboratory, heavy ion irradiation
Michael Siegal, Sandia National Laboratory, Thallium films
Ken Douglas, University of Colorado, biological nanolithography
Steven R. J. Brueck, University of New Mexico, interferometric nanolithography

TRANSITIONS

The development of HTS materials with periodic pinning arrays using interferometric lithography is under development for improving sensitivity of flux photoactivation. This may also result in a major improvement of current carrying capabilities in superconductors.

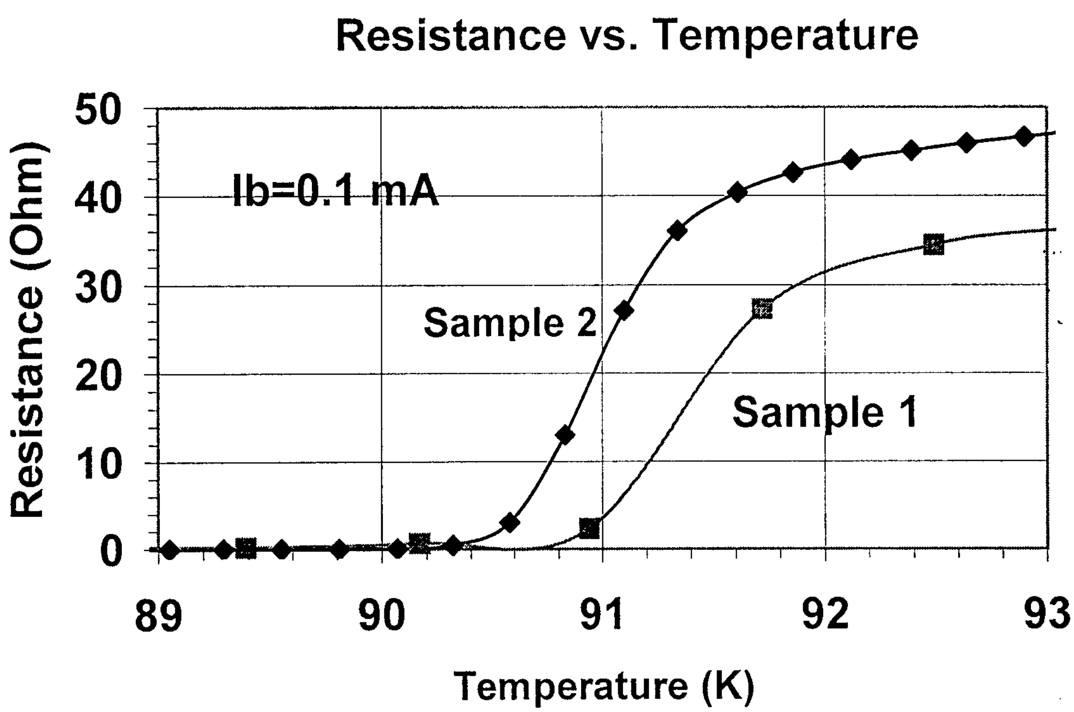

Resistance vs. Temperature
Resistance (Ohm)
50
40
30
20
10
0
Ib=0.1 mA
Sample 2
Sample 1
89
90
91
92
93
Temperature (K)

Fig. 1

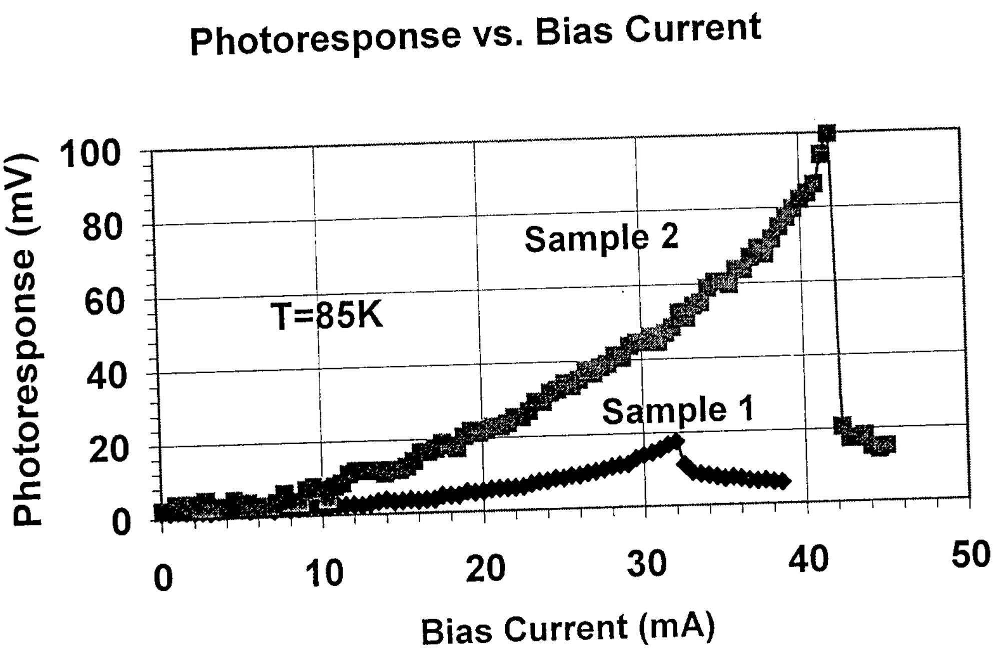

Photoresponse vs. Bias Current
Photoresponse (mV)
100
80
60
40
20
0
Sample 2
T=85K
Sample 1
0
10
20
30
40
50
Bias Current (mA)

Fig. 2

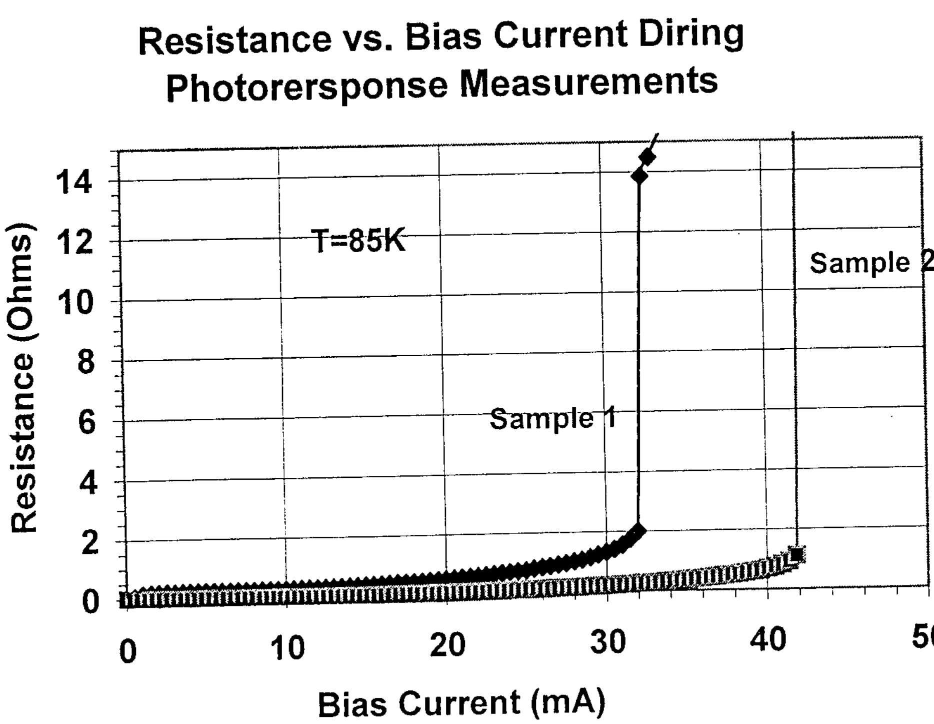

Resistance vs. Bias Current Diring
Photorersponse Measurements
Resistance (Ohms)
14
12
10
8
6
4
2
0
T=85K
Sample 2
Sample 1
0
10
20
30
40
50
Bias Current (mA)

Fig. 3

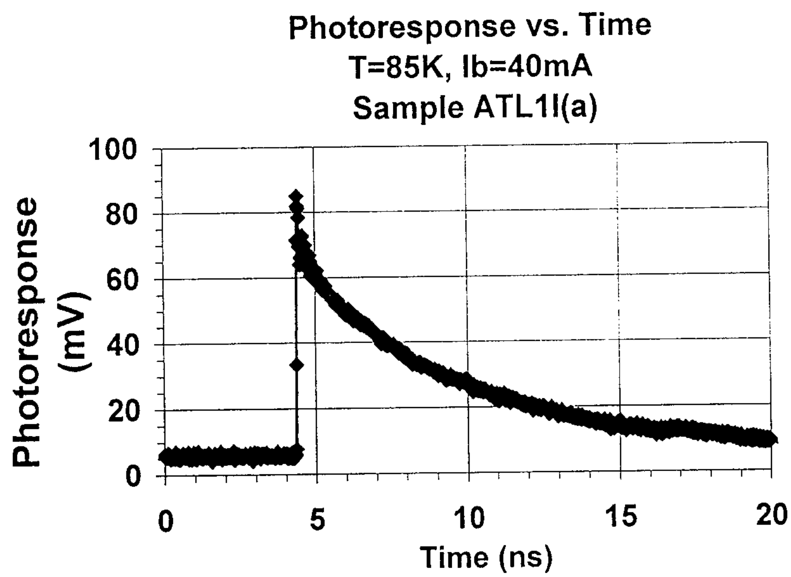
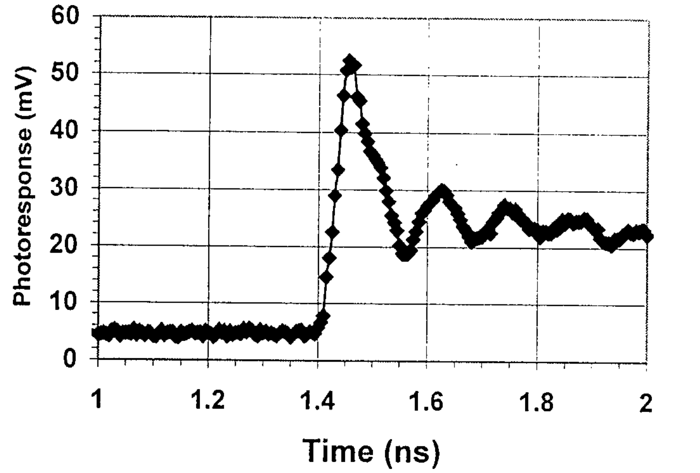

Photoresponse vs. Time
T=85K, Ib=40mA
Sample ATL1I(a)
100
80
60
40
20
0
Photoresponse (mV)
0
5
10
15
20
Time (ns)

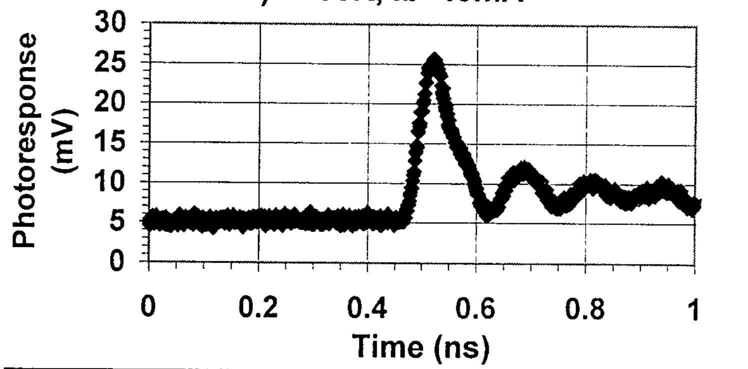
Fig. 4

Photoresponse vs. Time
Sample ATL1I(a)

a) T=83K, I = 60 mA



b) T=83K, Ib=40mA



c) T=83K, Ib=20mA

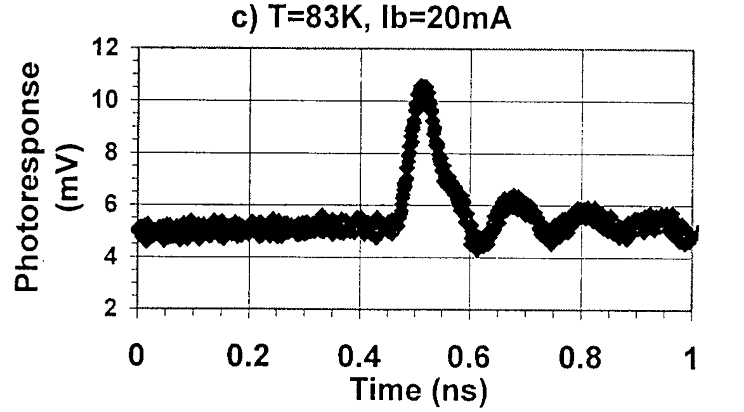
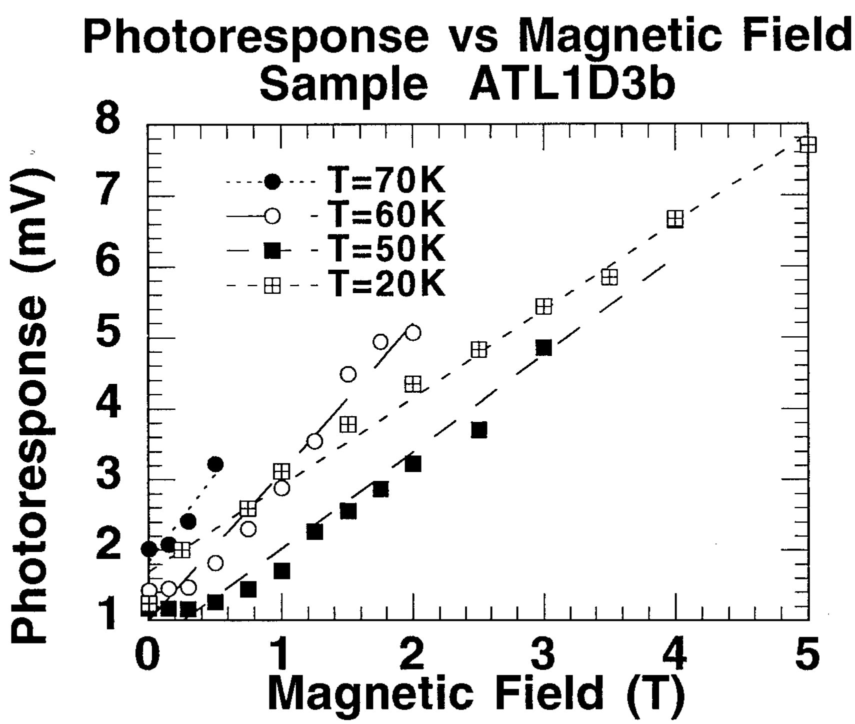


Fig. 5



Photoresponse vs Magnetic Field
Sample ATL1D3b
Photoresponse (mV)
Magnetic Field (T)
T=70K
T=60K
T=50K
T=20K
0
1
2
3
4
5
6
7
8

Fig. 6

APENDIX A
GENERAL DESCRIPTION OF THE PHOTORESPONSE

The real-time technique for the study of the photoresponse of a superconducting film to subpicosecond optical pulses comprises a read-out line with a bias tee and a fast oscilloscope. When illuminated by the optical pulse, the film undergoes an impedance change. The signal, seen on the oscilloscope, is related to the impedance transient via the electric transfer function of the circuit. Impedance transients shorter than the characteristic time of the transfer function are distorted so that neither proportions nor slopes of the transient are reproduced by the signal. An important simplification occurs if the shape of the impedance transient remains unchanged, in which case the magnitude of the signal M at maximum deviation is proportional to the corresponding magnitude of the impedance transient. If, additionally, the impedance change is small compared to its steady-state value and the time dependent portion of the current in the read-out circuit is small compared to the dc bias current, the signal can be expressed as

$$M = \max[E(t)] = K \max\left(I\,\Delta R(t) - \frac{d}{dt}[I\,L(t)] \right) \qquad (1).$$

Here K is the magnitude (absolute value) of the complex transfer function, I is the bias current, $\Delta R(t)$ and $L(t)$ are the time-dependent resistance change and inductance of the film, respectively. The term in right parentheses represents the effective signal source $S(t)$. Since the impedance of the superconducting film depends on the frequency, it is more convenient to use the spectral representation. The Fourier transform of $S(t)$ is

$$\widetilde{S}_{\omega} = I\left(R_{\omega} - j\omega L_{\omega}\right) = I\left[\mathrm{Re}(\widetilde{Z}_{\omega}) - j\,\mathrm{Im}(\widetilde{Z}_{\omega})\right] \qquad (2),$$

where Z is the impedance of the film and ω is the angular frequency of optical pulses. Assuming that the impedance of the film in the superconducting state is instantaneously controlled by the density of paired electrons and expressing the impedance in terms of the complex magnetic penetration length λ, one obtains

$$\widetilde{S}_{\omega} = (-1)\,\omega\,\mu_0 I \frac{l}{w\,d}\left\{\frac{d}{dn}\left[\mathrm{Im}(\widetilde{\lambda}_{\omega}{}^{2})\right] + j\frac{d}{dn}\left[\mathrm{Re}(\widetilde{\lambda}_{\omega}{}^{2})\right]\right\}\Delta n_{\omega} \qquad (3).$$

Here μ_0 is the permeability in vacuum, Δn_{ω} is the Fourier transform of the transient, $\Delta n(t)$, the paired-electron density, and l, w, and d are the film length, width, and thickness, respectively.

PHYSICAL MECHANISMS OF THE RESPONSE

In the absence of vortices created by a magnetic field (magnetic vortices), λ does not depend on the frequency in the interval determined by the reciprocal duration (100 fs) of the optical pulse. In this case λ simply becomes static London penetration depth $\lambda_L \propto$

$n(t)^{-1/2}$. When magnetic vortices are present in the film they may contribute to the impedance change caused by irradiation and, thus, to the photoresponse in different ways.

(i) Magnetic vortices reduce the density of equilibrium paired electrons by the amount of quasiparticles associated with the vortex cores. In a conventional s-wave superconductor with an isotropic energy gap this results in the magnetic field dependence of the London penetration depth $\lambda_L \propto (1-B/B_{C2})^{-1/2}$, where B_{C2} is the second critical magnetic field of the film.

(ii) A decrease of the density of paired electrons caused by optical pulses leads to a redistribution of the screening current, which circulates around each vortex core. The vortex becomes effectively larger which changes the restoring force that keeps the vortex at the pinning center. Since, due to the bias current, the vortex permanently experiences the Lorentz force, a sudden change of the restoring force sets on damped oscillations of the vortex near the pinning center. The oscillations contribute to both the real and imaginary parts of the impedance.

(iii) After optical excitation, a certain portion of pinned vortices can leave their pinning cites and move quasi-freely until they are re-captured at the same or other cites. This effect is very close to the regime called thermal activated flux flow and contributes mostly to the real part of the impedance change.

M.W. Coffey and J.R. Clem (PRL 67, 386 (1991)) derived the general expression for the frequency dependent penetration depth that accounts for the flux pinning and flux flow

$$\lambda^2(\omega,B,T) = \frac{\lambda_L^2(B,T) - \frac{j}{2}\delta_v^2(\omega,B,T)}{1 + j\dfrac{2\lambda_L^2}{\delta_{nf}^2}} \qquad (4).$$

Here the effective length δ_v and δ_{nf} corresponds to contributions of vortices and unpaired electrons, respectively, and λ_L describes the response of paired electrons. These three effective lengths are

$$\lambda_L^2 = \frac{\lambda_{L0}^2}{f}; \quad \delta_{nf}^2 = \frac{2\rho_n}{\mu_0\omega}\frac{1}{1-f}$$

$$\delta_v^2 = \frac{2}{\mu_0\omega}\frac{B\Phi_o}{\eta}\frac{\varepsilon + (\omega\tau_0)^2 + j(1-\varepsilon)\omega\tau_0}{1+(\omega\tau_0)^2}; \quad \tau_0 = \frac{\eta}{k_p}\frac{I_0^2(\nu)-1}{I_0(\nu)I_1(\nu)}; \quad \varepsilon = \frac{1}{I_0^2(\nu)}; \quad \nu = \frac{U}{2k_BT} \qquad (5),$$

where λ_{L0} is the London penetration depth at zero temperature and magnetic field, f is the fraction of superconducting electrons, Φ_0 is the flux quantum, ρ_n is the normal state resistivity, η is the flux viscosity, k_p is the restoring force, U is the random pinning potential, and I_0, I_1 are modified Bessel functions of the first kind. The two-fluid approximation results in the following field and temperature dependences

$$f=\left(1-\left(\frac{T}{T_c}\right)^4\right)\left(1-\alpha\frac{B}{B_{C2}(T)}\right)=1-\frac{n}{N_0};\quad B_{C2}(T)=B_{C2}(0)\frac{1-\left(\frac{T}{T_C}\right)^2}{1+\left(\frac{T}{T_C}\right)^2}$$

$$U=U_0\left(1-\frac{T}{T_C}\right)^{\frac{3}{2}};\quad k_p=k_{p0}\left[1-\left(\frac{T}{T_C}\right)^2\right]^2 \qquad (6),$$

where N_0 is the concentration of current carriers in the normal state, k_{p0} is the restoring force at T=0, U_0 is the random pinning potential at T=0, $B_{c2}(T)$ is the second critical magnetic field. The gap anisotropy of the cuprates is taken into account in the following manner. Because the gap vanishes in certain directions, the critical current in these directions extends down to zero. Consequently, the screening current around a vortex core will cause depairing at distances from the vortex center much larger than the coherence length. The amount of quasiparticles associated with the vortex core is then increased by a factor $\alpha \approx R/\zeta$. Here $R \approx (\Phi_0/B)^{1/2}$ is the mean distance between vortices and $\zeta(T) = \zeta_0/(1-T/T_C)^{1/2}$ is the effective coherence length (ζ_0 is the coherence length at zero temperature). Regardless of vortex motion, anisotropy of the gap should enhance the magnetic field dependence of the photoresponse contributed by paired electrons.

COMPARISON OF EXPERIMENTAL DATA AND COMPUTATION RESULTS

According to the assumption that the pinning potential and restoring force are both controlled by the instantaneous concentration of paired electrons, we express temperature dependences of k_p and U in terms of the fraction f of paired electrons in order to analyze their effect on the vortex response. We use the following analytic form for the qusiparticle transient

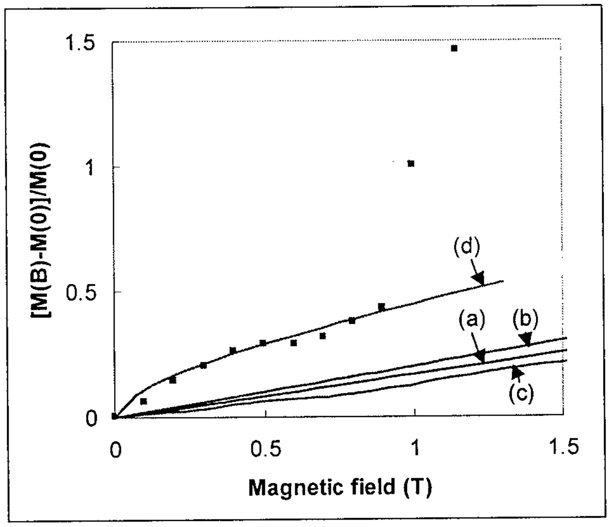
$$1-\frac{\Delta n(t)}{N_0}=\exp\left(-\frac{t}{\tau_f}\right)\frac{t^4}{\tau_r^4+t^4} \qquad (7),$$

where τ_f and τ_r are fall and rise times, respectively. Then we calculate the magnitude of the photoresponse as a function of magnetic field using Equations (1) – (6). Parameters used for the computation are listed in the Table 1.

Table 1. Material parameters and quasiparticle transient times

London penetration depth λ_{L0}, m	$1.4\cdot10^{-7}$
Flux viscosity η, N·sec/m	$2\cdot10^{-7}$
Restoring force at zero temperature k_{p0}, N/m^2	$2.1\cdot10^{4}$
Normal state resistivity ρ_n, Ohm·m	$3\cdot10^{-6}$
Random pinning potential U_0, eV	0.15
Second critical magnetic field at zero temperature $B_{C2}(0)$, T	114
Fall time of the quasiparticle transient τ_f, ps	3
Rise time of the quasiparticle transient τ_r, fs	300

The plot below shows the magnitude of the response signal computed for different limiting cases. The curve labeled (a) corresponds to an isotropic energy gap ($\alpha \equiv 1$) and non-moving vortices (k_{p0}, $U_0 \Rightarrow \infty$), the case (b) additionally includes oscillations of



vortices at pinning cites ($U_0 \Rightarrow \infty$), the case (c) includes flux pinning and flux flow for an isotropic superconductor, and (d) additionally accounts for the gap anisotropy. Note that the calculated magnitude of the ratio *[M(B)-M(0)]/M(0)* is multiplied by 5 for curves (a) through (c). Also shown are experimental data (filled squares) acquired at $T = 0.4T_C$. The curve (d) was fitted to the data by varying ζ_0 as the only one parameter. The value of 27 Å obtained from the fitting procedure reasonably corresponds to the coherence length in a-b plane reported by many authors for YBaCuO films.